

**A FIELD STUDY OF
GROUND DEPOSITION,
WIND DRIFT AND
BYSTANDER EXPOSURE FROM
AGRICULTURAL AIRCRAFT
SPRAY EMISSIONS**

by

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**A FIELD STUDY OF GROUND DEPOSITION, WIND DRIFT AND
BYSTANDER EXPOSURE FROM AGRICULTURAL AIRCRAFT
SPRAY EMISSIONS**

**ÉTUDE SUR LE TERRAIN DU DÉPÔT SUR LE SOL, DE LA PORTÉE
ÉOLIENNE ET DE LA DOSE REÇUE PAR UN TÉMOIN À LA SUITE
D'UNE OPÉRATION D'ÉPANDAGE AÉRIENNE AGRICOLE**

by/par

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National Aeronautical Establishment

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SUMMARY

Wind drift, deposition and bystander exposure measurements from agricultural aircraft and ground-rig spray emissions over rural terrain using conventional spray booms and atomizers are presented. A single line was treated. The formulations were aqueous oil emulsions to simulate herbicide applications and aqueous wettable powder emulsions to represent fungicide sprays. Meteorological conditions varied from 'calm' thermally unstable to near-neutral moderately windy (4.9 ms^{-1} at 4 m above ground). Time-integrated atmospheric droplet concentrations (dosage) were measured at breathing height to 500 m downwind and vertically to drift cloud top at 200 and 500 m downwind.

Analysis of field data disclosed initial ground deposit accounting for nearly 100% of the non-volatiles in the ground-rig emission, but only from 60 to 80% of the aircraft emission depending upon wind speed, in agreement with published data. When transformed into the equivalent operational multi-swath crosswind incremental spray scenario, the data indicated bystander dermal exposures to non-volatiles at 75 m downwind increasing from $150 \mu\text{g}$ for the first swath to $600 \mu\text{g}$ after 10 swaths in light winds (2.8 ms^{-1} at 4 m agl). At 200 m the measured drift cloud mass from the aircraft sprays varied from 1 to 2% of the emission in light winds. In this connection, 90° nozzle orientation on the aircraft resulted in greater wind drift than trailing orientation. The wettable-powder drift data revealed that at and beyond 75 m where spray evaporation was essentially complete, the dermal exposure could be less than from herbicide sprays due to the possibility of particle rebound from collecting surfaces.

The field study was conducted for the New Brunswick Departments of Agriculture and of Environment and was partly supported financially by the New Brunswick Department of Agriculture. As a result of this investigation, the N.B. Pesticides Advisory Board has reduced the setback distances for aerial herbicide and fungicide applications in that province from 75 m to 50 m.

RÉSUMÉ

On présente des mesures de la portée éolienne, du dépôt sur le sol et de la dose reçue par un témoin, à la suite d'une opération d'épandage. Le traitement a été effectué à partir d'un avion et d'installations au sol équipés de rampes de pulvérisation et du pulvérisateurs classiques. Une seule ligne de terrain a été traitée. Des émulsions d'huile dans l'eau ont été utilisées pour simuler les préparations herbicides et des émulsions aqueuses de poudre mouillable, pour simuler les préparations fongicides. Pour ce qui est des conditions météorologiques, la situation variait d'une atmosphère "calme" et thermiquement instable à une atmosphère presque adiabatique avec vents modérés (4,9 m/s à 4 m au-dessus du sol). La concentration des gouttelettes atmosphériques intégrée en fonction du temps (dose) a été mesurée, horizontalement, jusqu'à 500 m de lit du vent de la bouche (1,5 m en moyenne); et verticalement, jusqu'au sommet du nuage d'embrun, à 200 m et 500 m dans la direction du vent.

L'analyse des données relevées sur le terrain a révélé que presque 100% des substances non volatiles émises par les installations terrestres se déposent initialement sur le sol, contre seulement 60 à 80%, selon la vitesse du vent, dans le cas de l'émission par voie aérienne. Ces proportions concordent avec les données publiées. Une fois transformées pour correspondre au scénario opérationnel de pulvérisation continue à passages multiples perpendiculairement au vent, les données ont montré que, par vents légers (2,8 m/s à 4 m au-dessus du sol), un témoin se trouvant à 75 m dans le lit du vent reçoit par voie cutanée une dose qui varie de 150 μ g au premier passage à 600 μ g après 10 passages. Mesurée à 200 m dans la direction du vent, la masse du nuage d'embrun pulvérisé par voie aérienne variait de 1 à 2% de la masse émise par vents légers. À ce propos, en orientant la buse de l'avion à 90° vers le bas, on a obtenu une portée éolienne plus importante qu'en l'orientant vers l'arrière. Les données sur le dépôt de poudre mouillable ont révélé qu'à une distance égale ou supérieure à 75 m dans le lit du vent, à laquelle l'évaporation est presque complète, la dose reçue par voie cutanée pourrait être moins forte que dans le cas de la pulvérisation d'herbicides, car il est possible que les particules rebondissent à partir des surfaces collectrices.

L'étude sur le terrain a été effectuée pour le compte des ministères de l'Agriculture et de l'Environnement du Nouveau-Brunswick et elle a été subventionnée en partie par le ministère de l'Agriculture du Nouveau-Brunswick. À la suite de ces travaux, le *Pesticides Advisory Board* du N.-B. a réduit de 75 m à 50 m la distance tampon applicable à la pulvérisation d'herbicides et de fongicides par voie aérienne dans cette province.

CONTENTS

	Page
SUMMARY	(iii)
ILLUSTRATIONS	(vi)
1.0 INTRODUCTION	1
2.0 TEST SITE AND INSTRUMENTATION	1
2.1 Location and Characteristics	1
2.2 Sampling Grid Instrumentation	1
2.3 Meteorological Instrumentation	2
3.0 SPRAY FORMULATION AND DELIVERY	3
3.1 Spray Formulation	3
3.2 Spray Delivery	3
3.3 Chemical Analysis of Sampler Deposit	4
4.0 FIELD RESULTS	4
4.1 The Spray Scenario	4
4.2 Ground Deposition	5
4.3 Atmospheric Droplet Dosages at Breathing Height	5
4.3.1 Influence of Nozzle Type	5
4.3.2 Influence of Nozzle Orientation	6
4.3.3 Influence of Wind Speed	6
4.3.4 Influence of Aircraft Type	6
4.4 Bystander Dermal Exposure	6
4.5 Extrapolation of Single-Swath-Line Bystander Exposure to Multiple Swaths	6
4.6 Spray Budget	7
5.0 CONCLUSIONS	7
6.0 ACKNOWLEDGEMENT	8
7.0 REFERENCES	8

TABLES

Table		Page
1	Operating Conditions for GC Analysis	9
2	Part 1 — Experimental Spray Application Parameters	10
2	Part 2 — Experimental Spray Meteorological Conditions	11

TABLES (Cont'd)

Table		Page
3	Ground Deposit.	12
4	Bystander Exposure at 75 m from a Multiswath Aerial Application	13
5	Spray Budget.	14

ILLUSTRATIONS

Figure		Page
1		15
2(a)	Location of Test Site East of Ottawa	19
2(b)	Sampling Grid for Spray Drift Trials	20
2(c)	Typical Disposition of Ground Deposit Plates	21
3(a)	Normalized Crosswind Deposit from Ag-cat Sprays	22
3(b)	Normalized Crosswind Deposit from Pawnee Sprays	23
3(c)	Normalized Crosswind Deposit from Ground-rig Sprays	24
4(a)	Normalized Atmospheric Dosage of Non-volatiles at 1.5 m agl from Ag-cat Sprays	25
4(b)	Normalized Atmospheric Dosage of Non-volatiles at 1.5 m agl from Pawnee Sprays	26
4(c)	Normalized Atmospheric Dosage of Non-volatiles at 1.5 m agl from Ground-rig Sprays	27
5(a)	Normalized Bystander Dermal Exposure from Ag-cat Sprays	28
5(b)	Normalized Bystander Dermal Exposure from Pawnee Sprays	29
5(c)	Normalized Bystander Dermal Exposure from Ground-rig Sprays	30
6(a)	Normalized Vertical Dosage Profiles from the Ag-cat Sprays	31
6(b)	Normalized Vertical Dosage Profiles at 200 m from Pawnee Sprays	32
6(c)	Normalized Vertical Dosage Profiles at 200 m from Ground-rig Sprays	33

APPENDIX

Appendix		Page
1	Atmospheric Surface-Layer Structure During the Spray Trials	35

A FIELD STUDY OF GROUND DEPOSITION, WIND DRIFT AND BYSTANDER EXPOSURE FROM AGRICULTURAL AIRCRAFT SPRAY EMISSIONS

1.0 INTRODUCTION

The exposure of bystanders and other non-target receptors to windborne spray droplets is perceived to be a major hazard of aerial pesticide applications in Canadian agriculture. To deal with this problem, provincial regulators have established an hierarchy of set-back distances for a range of agricultural spray planes and formulations. Unfortunately, due to a paucity of high-quality field data in the literature on representative levels of atmospheric droplet concentrations and bystander dermal exposures from agricultural aircraft spray emissions, officials have had little to guide them in establishing buffer zone widths, frequently erring on the conservative side. However, with more realistic values based on actual field measurements, the provinces could increase the land area permitted to aerial treatment, thereby raising the economic viability of the spray operations while maintaining a high level of safety to personnel.

This report presents results of a controlled field experiment on deposition, wind drift and bystander exposure from agricultural aircraft spray emissions over rural terrain. The results comprise field data from Grumman/Schweizer Ag-cat and Piper Pawnee aircraft and from a ground rig, all fitted with conventional boom-nozzle systems. Meteorological conditions measured on-site during the trials varied from light-wind speed thermally unstable flow such as obtains on sunny 'calm' days to moderate-wind speed flow with slight lapse and inversion representing, respectively, morning and evening conditions on 'breezy' days. In each spray trial, the pilot flew a single line three times in a 15-minute interval in order to generate ensemble-averaged values of spray deposition, atmospheric concentration and dermal exposure. The Unsteady Aerodynamics Laboratory (UAL) extended the measurements to 500 m from the flight (spray) line in order that the data could be transformed to corresponding values for the ensemble of crosswind swaths flown in a normal field spray operation.

The UAL conducted 11 trials, devoting two of these to the ground rig, which sprayed only one swath per trial. The investigation was conducted for the New Brunswick (N.B.) Departments of Agriculture and of Environment.

2.0 TEST SITE AND INSTRUMENTATION

2.1 Location and Characteristics

The UAL chose a field site for the trials in a level rural area east of Ottawa. The field measures approximately 800 m E-W and 500 m N-S and for several kilometres to the west, the prevailing wind direction, the terrain is unbroken scrub land with scattered clumps of trees and wire perimeter fences (see Fig. 1(a)).

Within the field itself, a 300 m by 30 m row of trees on the western half of the northern boundary precluded tests for mean wind directions from NNW clockwise to NE. NAE's Flight Research Section had already partly cleared the site of brush for an independent study, and prior to the experiment in September 1984 the UAL cut the remaining brush. Subsequent meteorological measurements reported in Appendix I gave a value of aerodynamic roughness length of the site equal to 3 cm. The field was thus aerodynamically smoother than a mature crop field so that atmospheric droplet concentrations and dermal exposures measured during the trials would have been slightly larger than operational values.

2.2 Sampling Grid Instrumentation

The UAL established three spray lines to accommodate mean wind directions clockwise from ENE to NW. The spray lines are orthogonal to the field diagonals which comprise the sampling lines, as shown in Figure 2(a).

At each of the breathing height (1.5 m agl) sampler positions shown in Figure 2(b), the UAL deployed a gimbal-mounted chemical sampler fitted with a bivariate tail. These instruments are referred to as dosimeters, inasmuch as they measure time-integrated atmospheric droplet concentration, or dosage.

The UAL also deployed Rotorods* (RR) at 1.5 m agl at 50 and 200 m from the flight lines. Although the RR deposits are more difficult to quantify by GC than the dosimeter deposits, they require no isokinetic corrections as do those on the dosimeters. Consequently, the UAL corrected the dosimeter dosages to agree with the RR dosages at 50 and 200 m, a procedure which is equivalent to performing isokinetic corrections to the dosimeter readings with the aid of droplet-size spectra determined from microscopic analysis of the RR deposits. The corrections were only nominal, the largest measured value being 230% at 50 m from the flight line; at 200 m, the differences were negligible.

When converting RR deposits to dosages, the UAL was careful to measure the actual rim diameter of the spinning U-rod, as well as the rotational speed using a strobotac. The resulting volumetric sampling rates averaged 10% lower than the manufacturer's specifications.

The UAL raised an 18 m sampling mast at the position shown in Figure 2(b), which is 200 m from all three flight lines. Five levels of RRs were deployed on the mast to measure the vertical dosage profile in the spray drift cloud in Trials 4 to 11. Prior to Trial 4, the UAL measured the vertical dosage profile with dosimeters suspended from a captive blimp.

7.5-cm square stainless steel plates were deployed horizontally at ground vegetation height to measure deposition to 75 m from the spray line. 2.5 m intervals separated adjacent plate positions to 20 m, 5.0 m, thereafter (Fig. 2(c)).

The UAL also deployed clothed dressmaker forms fitted with 3.8 cm square stainless steel badges to measure bystander dermal exposure at 50, 75, 100 and 150 m from the flight line. Not all locations were serviced in every trial.

Photographs of the samplers are shown in Figure 1. All sampler deposits were analyzed by GC (see Section 3.3).

2.3 Meteorological Instrumentation

The UAL raised an 18 m meteorological mast at 50 m from the spray lines in the western half of the field, as shown in Figure 2(b). Three levels of MRI vector vanes** equipped with micro-bead thermistors were installed to measure turbulent momentum and heat flux as well as the mean vertical profiles of wind speed. The latter were used with the vertical droplet dosage profiles at 200 m to compute drift cloud mass. The former were employed to determine the thermal stability of the atmospheric surface layer during the trials, as well as to provide an estimate of the downward turbulent transfer velocity of drifting droplets.

The UAL also deployed a pair of MRI matched thermistors to determine the temperature gradient between 4.3 and 17.2 m above ground level (agl). When used with the mean wind speed gradient between these levels an alternative specification of stability emerges in the form of the gradient Richardson number at 8.5 m agl, the mean logarithmic height. Instrument difficulties, however, restricted these measurements to the last seven trials.

Detailed meteorological data are reported in Appendix I. All instrument output was multiplexed and stored on-site on analog magnetic tape with FM recorders and later analyzed using the UAL's HP 1000 minicomputer.

* Trade name. Manufactured by Ted Brown & Assoc.

** Propeller bivariate manufactured by Belfort Instrument Company. The fast temperature probes were developed at the UAL.

A photograph of the instrumented meteorological mast appears in Figure 1(d).

3.0 SPRAY FORMULATION AND DELIVERY

The UAL mixed the aircraft spray components in a recirculating tank system located by the spray pilot in a large field south of the test site, which he used as the aircraft landing strip. The formulation was pumped through a meter into the aircraft tank prior to a trial and pumped out again after the trial. The readings of this meter were used to compute, within an error of 5%, the volume of formulation applied per aircraft trial.

The volume applied by the ground rig was also determined by difference.

3.1 Spray Formulation

The UAL prepared an aqueous oil emulsion, comprising 4.8% non-volatiles by volume, to simulate the aqueous herbicide aircraft sprays in N.B., and an aqueous formulation of the wettable powder, Rovral*, comprising 3% non-volatiles, to simulate the aqueous fungicide aircraft sprays in N.B. Rovral is a relatively new fungicide which is mixed to approximately 50% lower concentration levels than the more common fungicides such as Manzate*, Dithane*, Dikar*, etc. Evaporated particle sizes are therefore expected to have been approximately 10% smaller in these trials than those from currently-used fungicides in N.B. This difference may be expected to have slightly lowered the measured deposition and dermal exposure in the first 100 m or so, raised the dermal exposure beyond 200 m or so and to have marginally raised the overall atmospheric particle concentrations relative to current usage. Agriculture Canada declined to issue a fungicide spray permit to the UAL other than for Rovral.

In the ground-rig trials, the UAL sprayed the herbicide simulant after a further 10-fold aqueous dilution corresponding to current mixing practice for ground rig applications vs. aircraft applications.

For all simulant trials, the formulation was seeded with a known volume of the tracer tris (2-ethyl hexyl) phosphate (TEHP) for GC-analysis purposes. In the Rovral trials, the GC measured Iprodione, a 50% constituent of Rovral.

3.2 Spray Delivery

The spray was applied by a Grumman/Schweizer Ag-cat and a Piper Pawnee aircraft as well as by a tractor-drawn ground rig, all configured with a conventional spray boom supporting diaphragm TeeJets fitted with either D8-45 or D6-45 disc cores in the case of the aircraft and 2080-16 flat spray tips in the case of the ground rig. The nozzles on the ground rig were pointed vertically down but varied from vertical to horizontal on the aircraft, in order to assess the effect of nozzle orientation on droplet deposition and drift.

In each trial, the line source strength in g m^{-1} of non-volatiles was determined from knowledge of the length of the spray line, the applied spray volume and the ratio of TEHP (or Iprodione) concentration to concentration of non-volatiles in the formulation. The corresponding application rates in 1 ha^{-1} were determined from knowledge of the reported swath widths for the Ag-cat (18 m) and Pawnee (14 m), but directly from the ground-rig calibration (swath width from the ground rig is about 11 m).

* Trade name.

3.3 Chemical Analysis of Sampler Deposit

The UAL dosimeter collected air samples on glass adsorber tubes packed with an approximately 1 cm length of Ni mesh coated with 1% OV-17. The adsorber tubes were approximately 76 mm long by 6.3 mm O.D. and 3.8 mm ID. The sampler, which contains a battery-operated diaphragm pump, draws ambient air through the adsorber tube at 1.5 to 2.5 lpm. Adsorbers were installed in each sampler in the laboratory and the flow rate for each dosimeter was measured before deployment in the field. After exposure during a field trial the adsorber tube was sealed with a polyethylene cap and remained in the sampler for transport to UAL for analysis.

Analysis was performed on a Varian Model 1400 Gas Chromatograph modified to accept adsorber tubes and provide means of thermal desorption of vapours. The GC was equipped with a Varian thermionic specific detector. Nickel 200 was used as a column material as well as for all plumbing lines and the body of the six-port switching valve. Operating conditions for the GC for the analysis of TEHP and Iprodione are given in Table 1. Adsorbers were analyzed according to the procedure described in Crabbe et al (1983).

The ground plates were collected after the spray trial and placed directly in covered polystyrene boxes. Care was taken to avoid contact between the surface of the plate and the storage box. In the laboratory the ground plates were washed with 10 ml of acetone and a 2 μ l aliquot of these washings was injected directly through the septum of the GC for analysis. The dermal exposure badges were washed with 4-5 mls of acetone and these washings were reduced to 100 μ l before injection of a 2 μ l aliquot into the GC.

Rotorod samplers were retrieved by hand and packed in carrying boxes for transportation to the laboratory.

Before analysis the three unexposed faces of the U-shaped rod were carefully swabbed with acetone to ensure that only the exposed-face deposit was analyzed. A 5 cm length of each of the rotorod legs was then washed with approximately 4 mls of acetone. The washings were reduced to 100 μ l and the standard analysis performed.

All washings were made with distilled in-glass grade acetone from Caledon Laboratories.

The gas chromatographic system was calibrated using 1.3×10^{-9} g/ μ l standard solution of tris (2-ethyl hexyl) phosphate in hexane or a 1×10^{-8} g/ μ l standard solution of Iprodione in hexane. Tris (2-ethyl hexyl) phosphate was acquired commercially. Analytical grade Iprodione was supplied by Agriculture Canada. Analytical peaks were recorded on a Spectro-Physics computing integrator.

4.0 FIELD RESULTS

4.1 The Spray Scenario

Details of the 11 spray scenarios are tabulated in Table 2 in terms of spray formulation, delivery, application rate and, finally, the meteorology. Note that the 2 m and 10 m windspeeds are 15-min mean values computed from surface layer similarity theory using the measured scaling parameters u^* and L from Appendix I (the 10 m wind speed corresponds to that reported from airports, which may be the only source of wind information available to the spray pilot). The angle θ associated with the 2 m wind speed value is the difference between the 15-min mean wind direction at this height and the perpendicular to the spray line. Ideally, it should be zero but, inasmuch as data correction factors would enter only as $\cos\theta$, the slight departures, with the exception of Trial 8, from ideal shown here are not serious (the Trial 8 wind direction at 10 m was closer to the ideal than at 2 m). The tabulated temperature differences (ΔT) are 15-min mean values between 4.3 and 17.2 m agl. Values less than -0.00986 ($17.2-4.3$) = -0.127°C indicate thermally unstable conditions (positive heat flux); values larger than -0.127°C indicate thermally stable conditions (Trials 3 and 11). The actual degree

of stability is tabulated in Appendix I in terms of the Obukhov length L based on measured values of turbulent momentum and heat flux. The tabulated temperatures are 15-min mean values measured at 4.3 m agl. Relative humidity was not measured, but was judged to have average daytime values throughout the investigation inasmuch as none of the trials occurred in early morning or late evening.

4.2 Ground Deposition

The crosswind ground deposit profiles from the 11 trials are plotted in Figure 3. The ordinate is (plate) deposit in g m^{-2} divided by line source strength in g m^{-1} such that the crosswind integral is the fraction of the emission which is initially deposited, i.e. to within 5 m downwind of the reported vehicle swath width, as well as to within 75 m of the flight (swath) line. Cubic spline fits were employed for the integration and the results are tabulated in Table 3.

The initial deposit varies from approximately 60% in 2 m wind speeds of 4 ms^{-1} to approximately 80% in 2 ms^{-1} wind speeds. Apart from this trend, there is little systematic variation. The UAL attributes this result partly to experimental scatter, but mainly to proximity of the nozzles to the ground. The aircraft were observed to fly in ground effect with the wheels one to two feet agl (Fig. 1) so that the bulk of the emission was deposited rather than entrained into the wing tip vortices. In this connection, most of the material is deposited within the initial zone, i.e. within 5 m of the downwind edge of the reported swath width, particularly in the light-wind trials. Maybank et al (1978) report about 60% initial deposit from their aircraft trials in 3 ms^{-1} wind speeds.

The ground rig nozzles were even closer to the ground than those on the aircraft, resulting in nearly complete deposit within 75 m of the spray line, despite the relatively high wind speeds present.

The abnormally high deposit measured in Trial 10 is judged to be within experimental error. This is not the case in Trial 7, which was the first Rovral trial. It is possible that the material was incompletely mixed in the aircraft tank resulting in a Rovral concentration below the value based on the known composition of the mix. As a result, no experimental deposition or dosage data are plotted for Trial 7. The other two Rovral trials appear satisfactory however.

4.3 Atmospheric Droplet Dosages at Breathing Height

The time-integrated concentration of non-volatiles measured at 1.5 m agl are plotted in Figure 4 after normalization to unit line source strength, i.e. per g m^{-1} . The ordinate is the natural logarithm of the dosage divided by the source strength. The experimental points beyond $x = 25 \text{ m}$ are fitted by least squares to log-linear curves in order to reveal trends which are masked by experimental scatter. These curves can be used to transform the data into corresponding results for a multi-swath spray scenario. An example will be given in Section 4.5. To convert plotted values of droplet dosage to oral exposure, multiply by the volumetric breathing rate in lpm and the line source strength in g m^{-1} . The formula for line source strength in terms of application strength is line source (g m^{-1}) = $\text{g ha}^{-1} / \frac{10000}{\text{SW}}$, where SW is the swath width in metres.

The above data reflect the influences of wind speed, nozzle type and orientation and aircraft type. These are briefly discussed below.

4.3.1 Influence of Nozzle Type

The D8-45 operates at a higher volume flow than the D6-45 and so generates larger droplets which might reasonably be expected to remain airborne for shorter times. From a comparison of the average of the curves for Trials 1 and 2 with the curve for Trial 3, a process which removes the influence of wind speed and nozzle orientation, this expectation is seen to be true. The atmospheric dosage from the D6-45 emission decreases less rapidly with distance than that from the D8-45 emission.

4.3.2 Influence of Nozzle Orientation

When the nozzle is oriented normal to the flight path, the emission is subject to intense crosswind shear, which is absent in the case of trailing orientation. The result is finer droplets which remain airborne longer. Supporting evidence is provided by the higher airborne dosages in Trial 1, with 90° nozzle orientation, than in Trial 2 with 0° orientation. In fact, if the wind speed in these trials were the same, this difference might even be larger.

4.3.3 Influence of Wind Speed

The effect of increasing wind speed is to raise the turbulent transfer velocity (see Appendix I) proportionately so that the overall influence of wind speed should be small. That this is the case is seen from the data of Trials 3 and 4, which yielded, within experimental scatter, similar atmospheric dosage data despite wind speeds differing by 60%.

4.3.4 Influence of Aircraft Type

The Ag-cat aircraft might be expected to yield higher wind drift due to the entrainment of fine droplets into the upper wing-tip vortices. However, when the regression curves for Trials 4 and 5 are examined and the difference due to different nozzle type is removed (see Section 4.3.1), the result is nearly identical slopes. Consequently, to within experimental error, the present data reveal no influence on wind drift of aircraft type between the Ag-cat and Pawnee.

4.4 Bystander Dermal Exposure

The dermal exposure in μg of impacted non-volatiles on 3500 cm^2 of frontal area is plotted in Figure 5 after normalization to unit line source strength. The ordinate is the natural logarithm of the exposure divided by the line source strength in g m^{-1} . The exposure area is somewhat arbitrary; other values may be chosen after multiplying the impacted masses by the ratio of the areas, inasmuch as the plotted data were obtained by averaging the badge deposits on the dressmaker forms and linearly scaling the result up to 3500 cm^2 . Not unexpectedly, the highest bystander dermal exposures result from aircraft spray emissions in high wind speeds (Trial 2).

The tabulated data are fitted by least squares to log-linear curves which may be used to transform the data into corresponding results for a multi-swath spray. The example of Section 4.5 will elaborate.

The dermal exposure measured in Rovral Trials 8 and 9 is lower than in the simulant trials. The UAL believes this result arises from the dry particulate nature of the evaporated wettable powder spray. Dry particles tend to rebound from hard collecting surfaces whereas liquid particles will deposit due to surface tension forces. This difference does not appear in the dosimeter deposits, which were obtained by aspirating an adsorber tube, nor does it apply to the initial Rovral deposits where the particles were still in liquid form.

4.5 Extrapolation of Single-Swath-Line Bystander Exposure to Multiple Swaths

The first swath largely determines the oral and dermal exposure of a bystander in the downwind vicinity of the field boundary inasmuch as in incremental crosswind applications, subsequent spray swaths are progressively further upwind. The bystander exposure at a given distance from the boundary, resulting from multiple swaths, may be computed from the regression curves of Figures 4 and 5 by adding to the base figure the curve-fit values obtaining at the given distance successively incremented by one swath width. This result must be further adjusted for application strength of non-volatiles and vehicle swath width. The formula for this is

$$\text{operational spray bystander exposure} = \text{computed exposure} \times \text{g ha}^{-1} / \frac{10000}{\text{swath width (m)}}$$

As an example, results for the dermal and oral exposure at 75 m from a 10-swath Ag-cat spray are given in Table 4. The application strength in this example is 50 g of non-volatiles per ℓ in 30 ℓ ha $^{-1}$ and the mean wind speed at 2 m agl is 2.2 ms $^{-1}$ (Trial 4). The bystander breathes at 20 ℓ pm and has an effective exposure area of 3500 cm ^{2} .

The example results in Table 4 indicate that beyond 10 swaths very little additional exposure per swath occurs. Overall, the oral exposure is negligible compared to the dermal exposure.

4.6 Spray Budget

The spray budget comprises the fractional deposition and wind drift components at selected distances from the spray line. The wind drift is computed from the measured vertical profiles of droplet dosage and wind velocity using the method of Crabbe et al (1982). A selection of dosage profiles at 200 m is plotted in Figure 6, which typically feature two bumps. The UAL ascribes these feature to spray plane vortex rebound carrying material downwind inasmuch as they are largely absent in the case of the ground-rig sprays.

The measured and computed budget components are given in Table 5. Due to difficulties with the blimp-supported dosimeters, no wind drift data are shown for Trials 2 and 4 although some dosage profiles from these trials are shown in Figure 6(a) for illustrative purposes. Drift data for the remaining trials were measured from RR profiles. Except in the slightly stable ground rig spray (Trial 11), the RR profile did not quite encompass the entire depth of the drift cloud at 200 m. Before using these profiles in the drift computation, they were assigned an approximate upper limit with the aid of the earlier blimp profiles at 200 m.

The lowest values of wind drift occur in the light-wind speed aircraft sprays (Trials 5-9) and in the ground-rig sprays. However, the measured wind drift in the final two Rovral sprays (Trials 8 and 9) may be too low due to the inability of the RR to collect the dry particles. In anticipation of this problem the UAL deployed two RRs at 1.5 m agl at 200 m in the Rovral trials, one treated with a film of silicone grease on the collecting surfaces, and one untreated. The modified rod collected 4.7 times as much as the unmodified rod, and this ratio was then applied to the entire profile, averaged over Trials 8 and 9 which had essentially the same meteorology, spray aircraft nozzle and application strength. The result of integrating the product of this corrected dosage profile and the component of mean wind speed normal to the spray line gave 0.2% for the wind drift component at 200 m. This value is close to that computed in the light-wind speed simulant trial (No. 6) indicating both that the correction applied to the Rovral dosage profiles is not unreasonable and that very light-wind speed regimes reduce wind drift beyond the immediate vicinity of the swath.

The data of Table 5 reveal that in moderately unstable conditions, the wind drift at 200 m from an agricultural aircraft spray is 9% of that at 5 m from the swath edge in a 2 m wind speed of 2 ms $^{-1}$ (Trial 5). Maybank et al (1978) observed a value of 5% in slightly higher wind speeds. Computations using a Markov chain model (Crabbe and Curry, 1983) predict wind drift at 200 m equal to 0.06% and 43% of the emission for D6-46 and TeeJet nozzles, respectively, suggesting that the D8-45 atomizers at 45°, which gave 1.4% wind drift at 200 m, in Trial 5 produced smaller droplets than the D6-46 atomizer.

5.0 CONCLUSIONS

Eleven controlled field trials on deposition, wind drift and bystander exposure from agricultural aircraft and ground rig spray droplet emissions have been described. The investigation was conducted to provide field data to aid toxicologists in determining set-back distances from agricultural aircraft pesticide spray applications in N.B.

The following conclusions are drawn:

- 1) The initial deposition, from upwind of the swath to 5 m downwind of the swath edge, is about 80% independent of aircraft type, but reduces to about 60% with increase wind speed at 2 m agl from 2 ms^{-1} to 4 ms^{-1} . Maybank et al report about 60% initial deposit in 3 ms^{-1} winds.
- 2) Light winds of the order of 1 ms^{-1} at 2 m agl result in less than 1% wind drift at 200 m downwind.
- 3) The bystander dermal exposure to wind-blown spray droplets increases with wind speed but falls rapidly with distance. At 75 m in 2 ms^{-1} winds at 2 m agl it typically increases from approximately $150 \mu\text{g}$ for the first (upwind) swath to approximately $600 \mu\text{g}$ after 10 swaths in a multiswath field spray. The oral exposure is negligible by comparison and less sensitive to wind speed.
- 4) 90° nozzle orientation on the aircraft results in higher atmospheric droplet concentrations than trailing orientation, presumably because of production of finer droplets.
- 5) The initial deposition from the ground rig is almost 100% in all wind speeds; less than 1% is airborne at 200 m.
- 6) Bystander dermal exposure to wettable powder sprays is less than from liquid sprays, probably because of dry particle rebound. Further work is required to determine the difference between dry particulate deposition on metal bystander badges and exposed skin, etc.

6.0 ACKNOWLEDGEMENT

This study was partly supported financially by the New Brunswick Department of Agriculture under a letter agreement from Mr. Andrew of 14 September 1984. The authors gratefully acknowledge the assistance of Ms. Nancy Muir of Health and Welfare Canada in providing equipment for the measurement of bystander dermal exposure.

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NRC Assoc. Committee on Scientific Criteria, NRCC No. 20647, 1983.

TABLE 1
OPERATING CONDITIONS FOR GC ANALYSIS

	TEHP	Iprodione
Column	0.5 m 5% SE-30 on Supelcoport 80-100 mesh	0.5 m 5% SE-30 on Supelcoport 80-100 mesh
Adsorber 2	1% OV-17 on Ni mesh	1% OV-17 on Ni mesh
Temperatures		
Column	210°C	190°C
Detector	300°C	300°C
Switching Valve	200°C	200°C
Ads 1 Heater	290°C	290°C
Septum	245°C	245°C
Carrier Gas	N ₂ UHP at 45 ccpm	N ₂ UHP at 45 ccpm
Air Flow	125 ccpm	125 ccpm
H₂	4.5 ccpm	4.5 ccpm
Bead Current	6.0	6.0

TABLE 2 - PART 1
EXPERIMENTAL SPRAY APPLICATION PARAMETERS

Trial	Date and Time (EST)	Aqueous Formulation	% Non-volatiles by Mass	Delivery Vehicle, Speed (ms^{-1}), Nozzle and Orientation	Application Rate (l ha^{-1}) of Formulation	Application Rate (kg ha^{-1}) of Non-volatiles
1	28 Sept/84 at 1707h	Oil emulsion	4.8	Ag-cat at 46 ms^{-1} D8-45 at 90°	33.3	1.58
2	4 Oct/84 at 0932h	Oil emulsion	4.8	Ag-cat at 47 ms^{-1} D8-45 at 0°	32.6	1.55
3	4 Oct/84 at 1618h	Oil emulsion	4.8	Ag-cat at 47 ms^{-1} D8-45 at 45°	22.7	1.08
4	6 Oct/84 at 1645h	Oil emulsion	4.8	Ag-cat at 46 ms^{-1} D8-45 at 45°	23.2	1.10
5	10 Oct/84 at 1504h	Oil emulsion	4.8	Pawnee at 44 ms^{-1} D8-45 at 45°	38.0	1.80
6	11 Oct/84 at 1022h	Oil emulsion	4.8	Pawnee at 45 ms^{-1} D8-45 at 45°	37.2	1.76
7	11 Oct/84 at 1311h	Rovral	3.3	Pawnee at 45 ms^{-1} D8-45 at 45°	37.2	1.23
8	12 Oct/84 at 1221h	Rovral	2.9	Pawnee at 45 ms^{-1} D8-45 at 45°	37.2	1.09
9	12 Oct/84 at 1411h	Rovral	2.9	Pawnee at 45 ms^{-1} D8-45 at 45°	37.2	1.09
10	17 Oct/84 at 1311h	Oil emulsion	0.5	Ground rig at 1.8 ms^{-1} 2080-16 at 90°	223	1.18
11	17 Oct/84 at 1705h	Oil emulsion	0.5	Ground rig at 1.8 ms^{-1} 2080-16 at 90°	223	1.18

TABLE 2 - PART 2
EXPERIMENTAL SPRAY METEOROLOGICAL CONDITIONS

Trial	Wind Speed (ms^{-1}) at 2 m agl	Angle Between Wind Direction and Sampling Line ($^{\circ}$)	Wind Speed (ms^{-1}) at 10 m agl	$\Delta T(^{\circ}\text{C})$	T($^{\circ}\text{C}$)
1	3.0	5.5	4.3	-0.291	14
2	4.2	19	5.8	-0.360	4
3	3.4	13	4.7	-0.119	8
4	2.2	17.5	3.5	-0.371	10
5	2.1	26	3.3	-0.358	14
6	0.7	13	1.3	-0.188	11
7	1.4	5	2.0	-0.264	12
8	0.9	47	1.4	-0.370	16
9	0.9	7.5	1.5	-0.499	21
10	3.8	16	5.3	-0.616	14
11	3.5	13	4.8	0.266	13

TABLE 3
GROUND DEPOSIT

Trial	Vehicle	2 m Wind Speed ms⁻¹	% Initial Deposit	% Deposit to 75 m
1	Ag-cat	3.0	66.1	81.9
2	Ag-cat	4.2	61.1	68.4
3	Ag-cat	3.4	54.5	65.3
4	Ag-cat	2.2	79.0	86.3
5	Pawnee	2.1	85.0	94.0
6	Pawnee	0.7	62.3	65.0
7	Pawnee	1.4	23.3	24.7
8	Pawnee	0.9	63.5	64.1
9	Pawnee	0.9	73.5	73.5
10	Ground rig	3.8	106.7	110.9
11	Ground rig	3.5	8.3	85.5

TABLE 4

BYSTANDER EXPOSURE AT 75 m FROM A MULTISWATH AERIAL APPLICATION

Swath No.	Distance (m)	Unit Dermal Exposure (μg)	Operational Dermal Exposure (μg)	Unit Oral Exposure (μg)	Operational Oral Exposure (μg)
1	75	54	147	0.3	0.7
2	93	96	259	0.5	1.3
3	111	127	344	0.7	1.8
4	129	152	409	0.8	2.2
5	147	170	459	0.9	2.6
6	165	184	497	1.0	2.9
7	183	195	526	1.1	3.1
8	201	203	548	1.2	3.4
9	219	209	565	1.3	3.5
10	237	214	578	1.4	3.7

TABLE 5
SPRAY BUDGET

Trial	Initial Deposit (%)	Deposit to 75 m (%)	Wind Drift at 200 m (%)
1	66.1	81.9	
2	61.1	68.4	
3	54.5	65.3	
4	79.0	86.3	
5	85.0	94.0	1.4
6	62.3	65.0	0.2
7	23.2	24.7	
8	63.5	64.1	
9	73.5	73.5	0.2
10	106.7	110.9	0.6
11	83.3	85.5	0.5

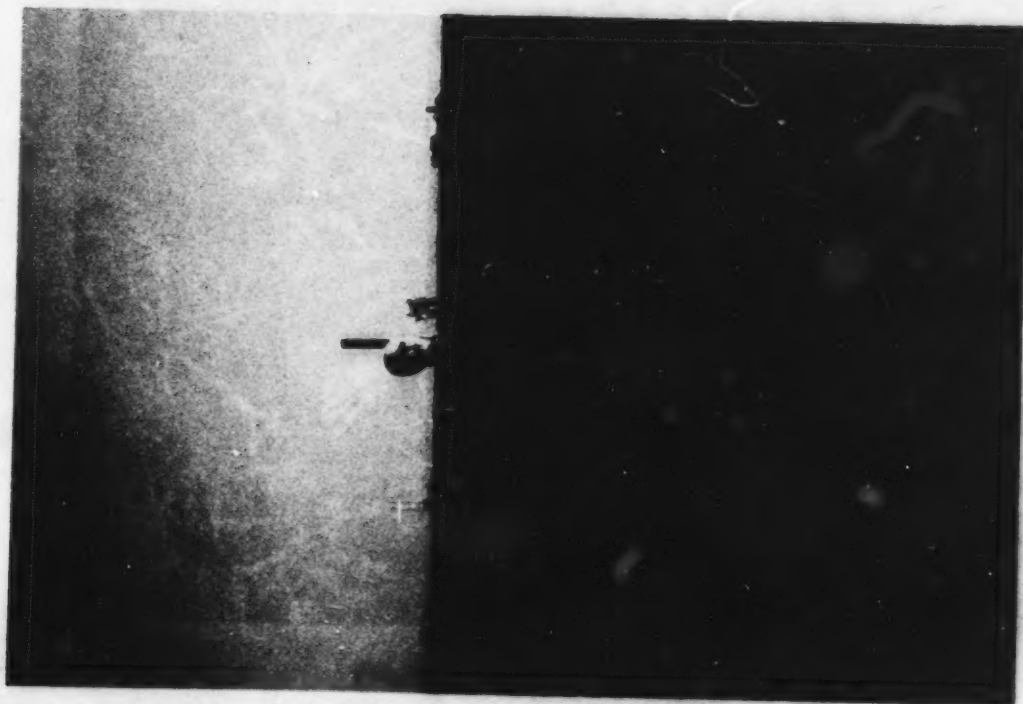


(a) TYPICAL AERIAL AGRICULTURAL SPRAY AT TEST SITE

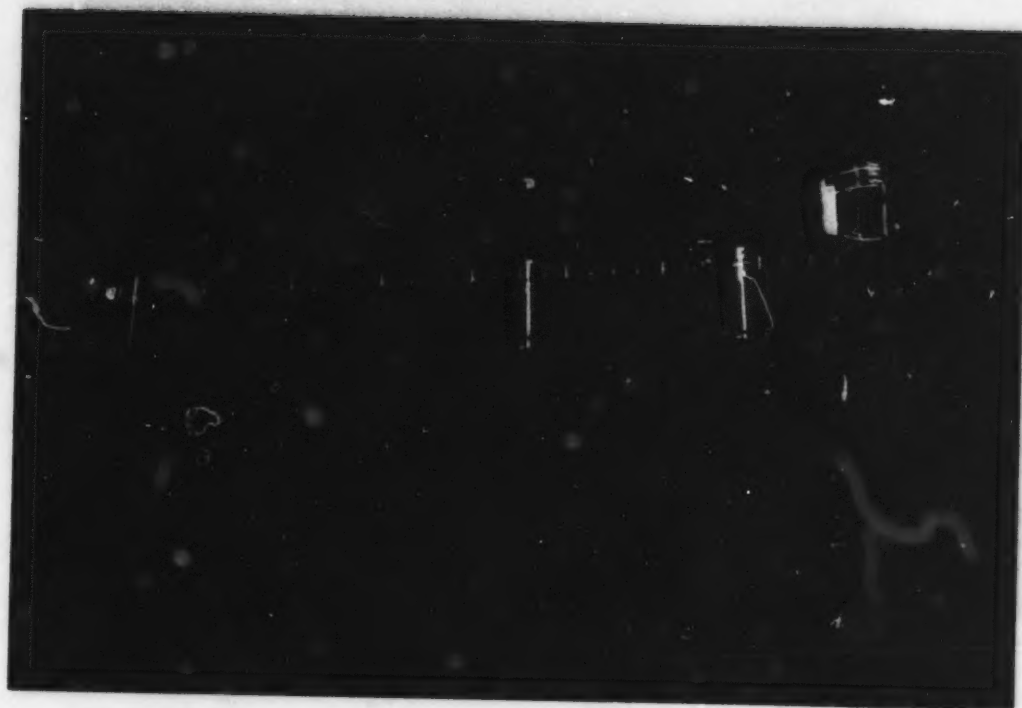


(b) EXPOSED GROUND DEPOSIT PLATE

FIGURE 1 (Cont'd)



(c) INSTRUMENTED BYSTANDER MODEL



(d) 18 m METEOROLOGICAL MAST

FIGURE 1 (Cont'd)

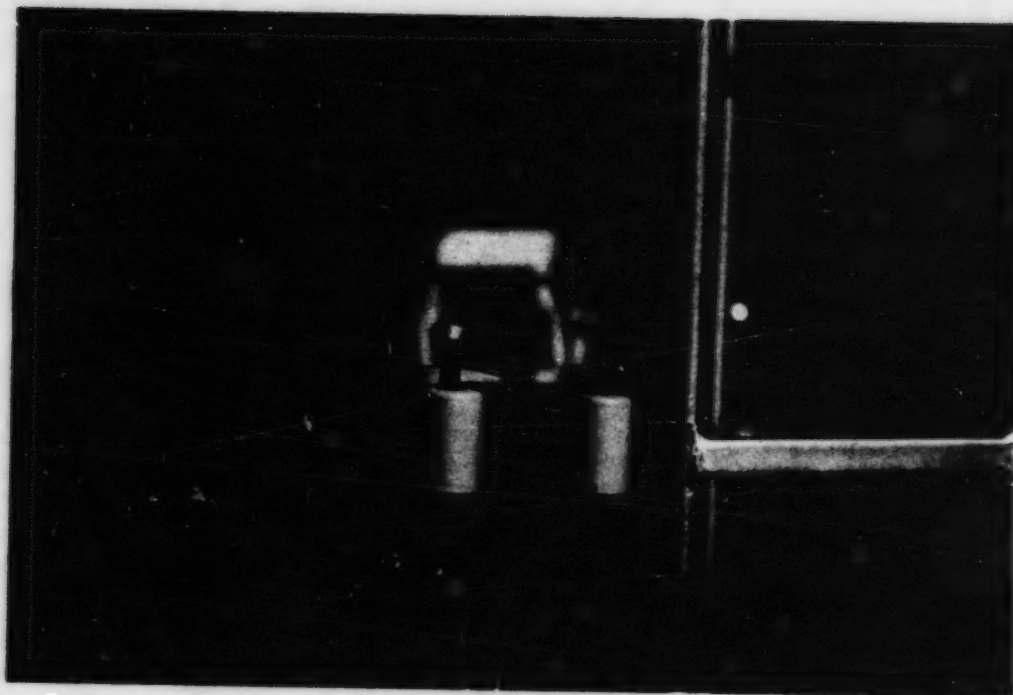


(e) PAWNEE SPRAYING (NOTE PYLONS MARKING THE SPRAY LINE)

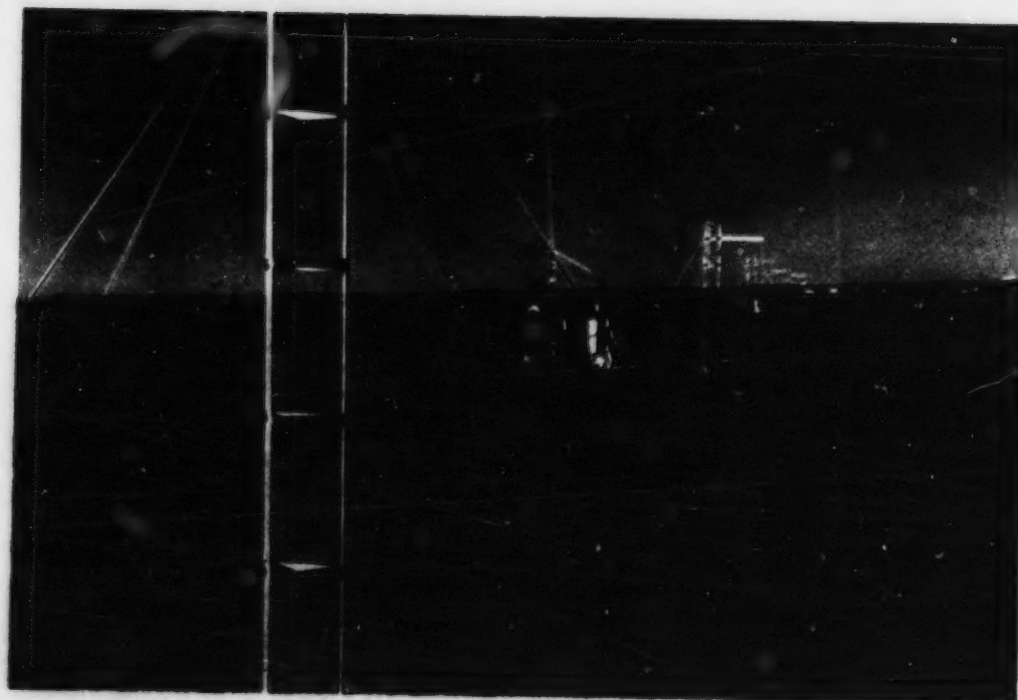


(f) PAWNEE SPRAYING (NOTE PYLONS MARKING THE SPRAY LINE)

FIGURE 1 (Cont'd)



(g) ROTOROD SAMPLERS



(h) GIMBALLED CHEMICAL SAMPLERS WITH BYSTANDER MODELS AND
18 m SAMPLING MAST IN BACKGROUND

FIGURE 1

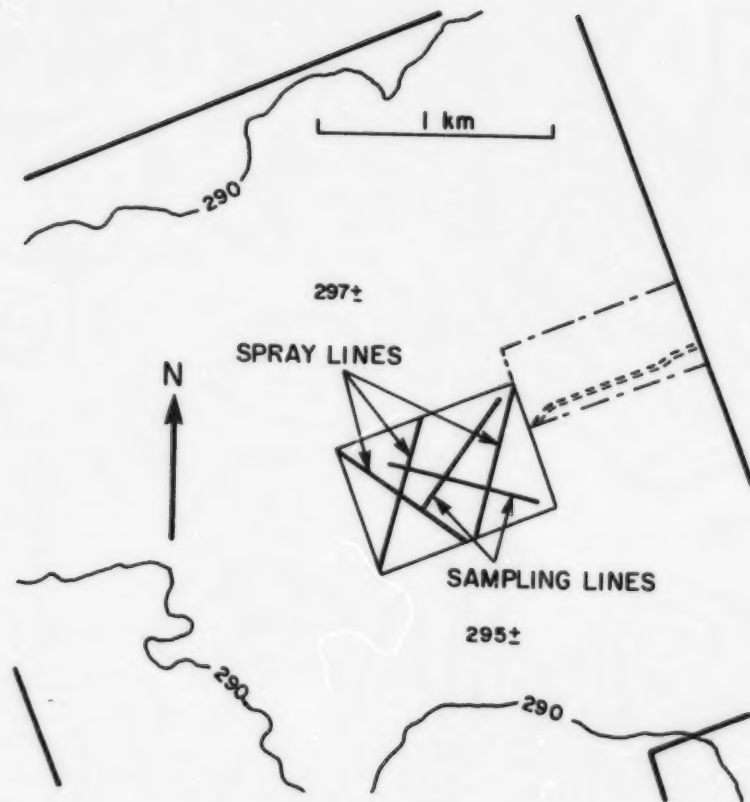


FIG. 2(a): LOCATION OF TEST SITE EAST OF OTTAWA

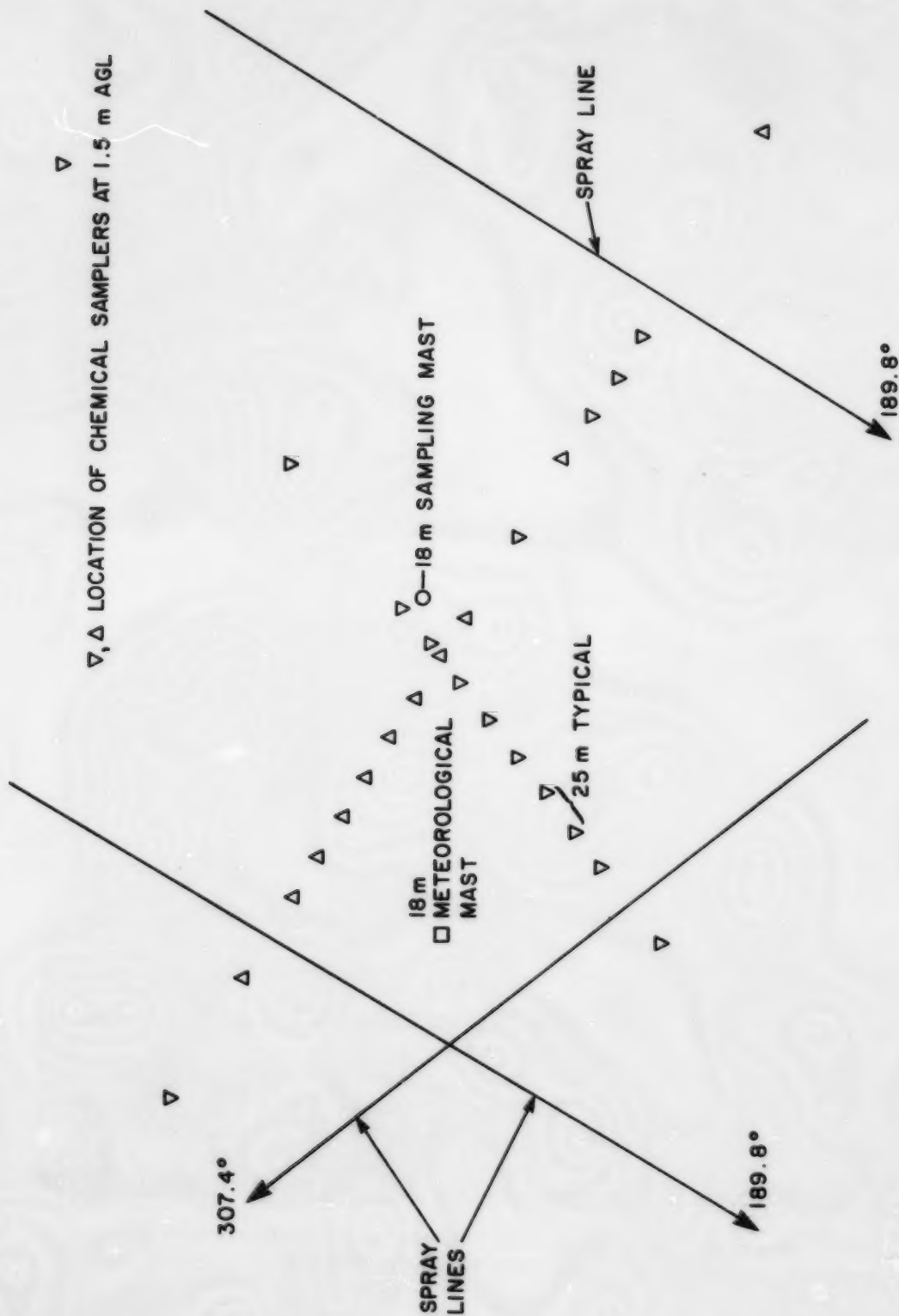


FIG. 2(b): SAMPLING GRID FOR SPRAY DRIFT TRIALS

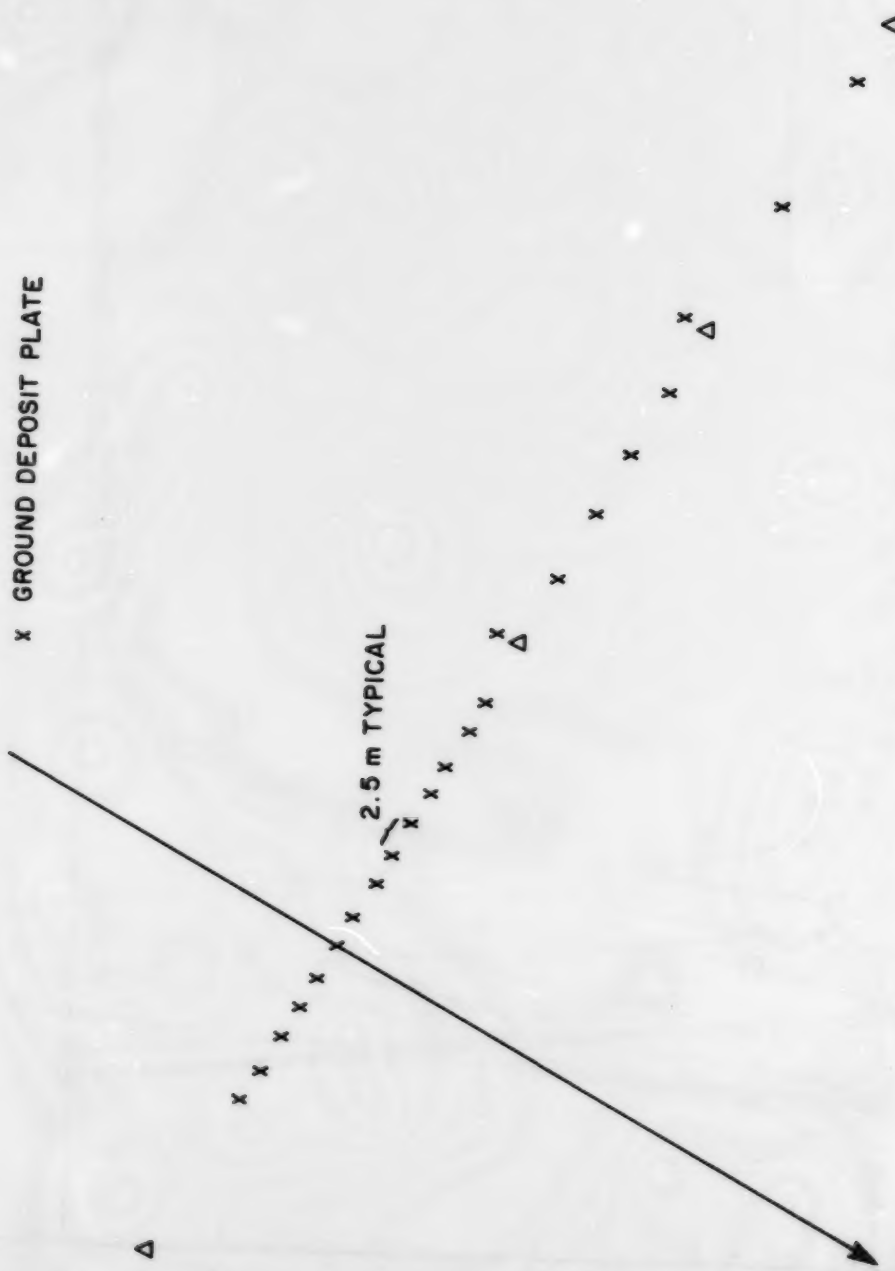


FIG. 2(c): TYPICAL DISPOSITION OF GROUND DEPOSIT PLATES

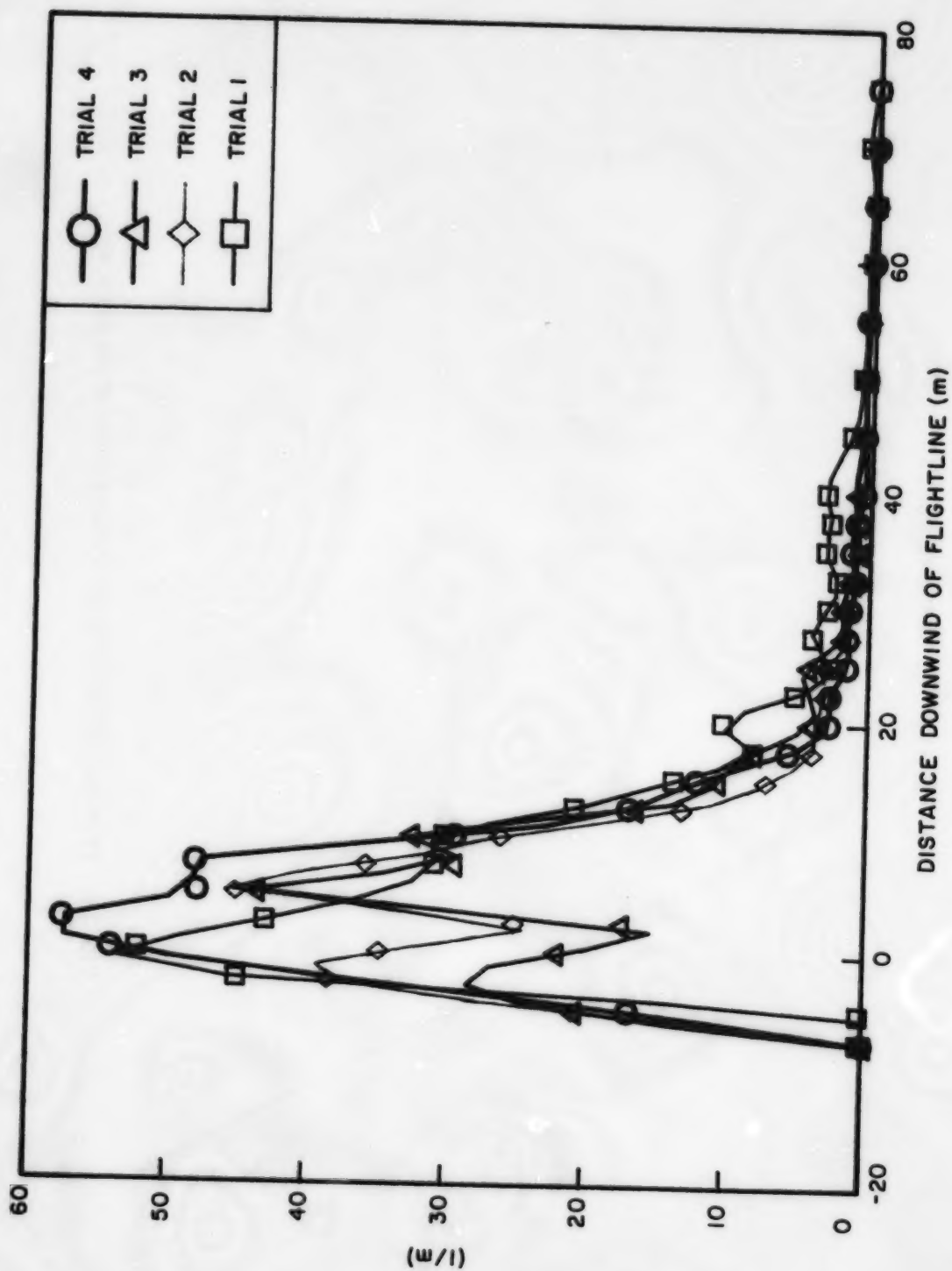


FIG. 3(a): NORMALIZED CROSSWIND DEPOSIT FROM AG-CAT SPRAYS

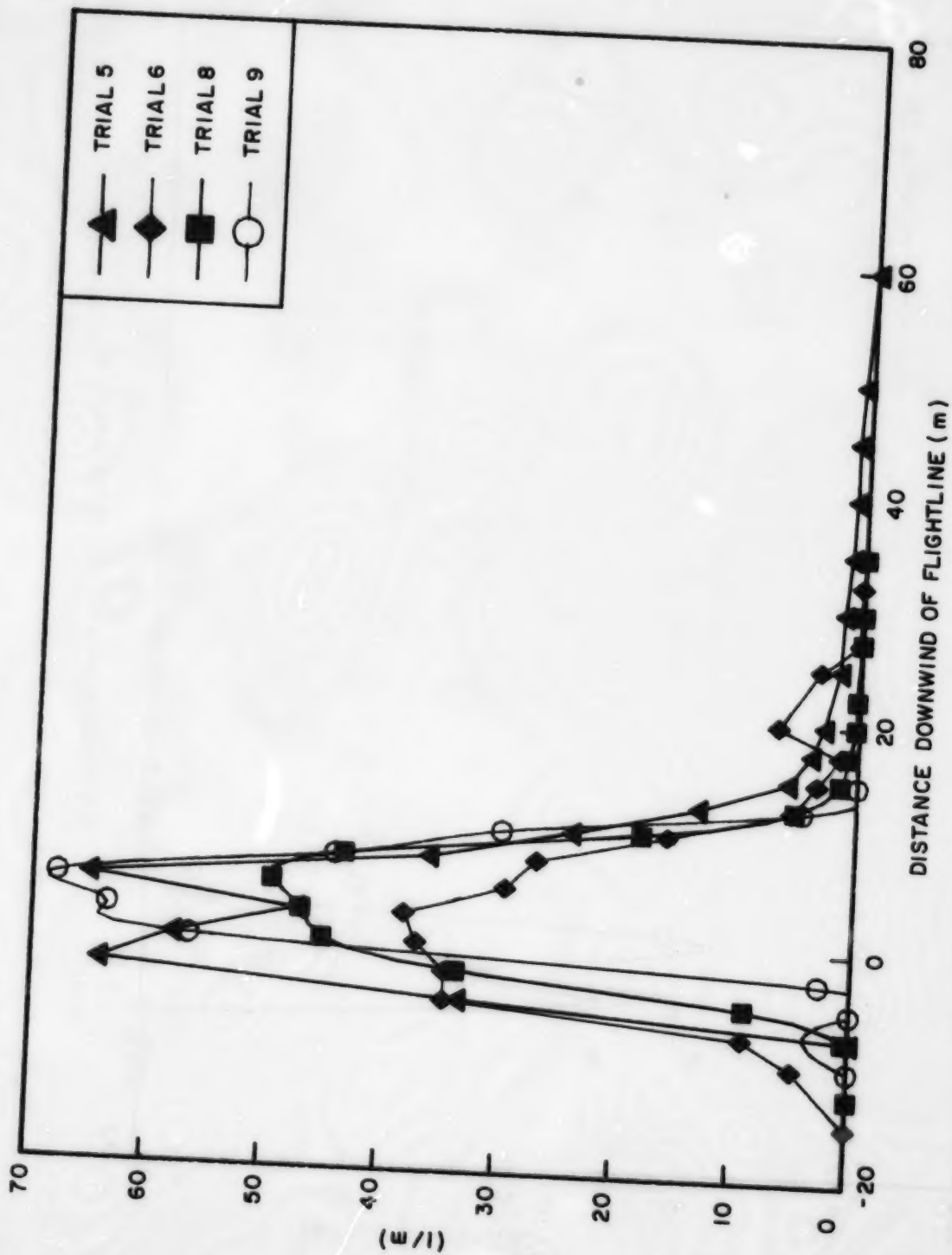


FIG. 3(b): NORMALIZED CROSSWIND DEPOSIT FROM PAWNEE SPRAYS

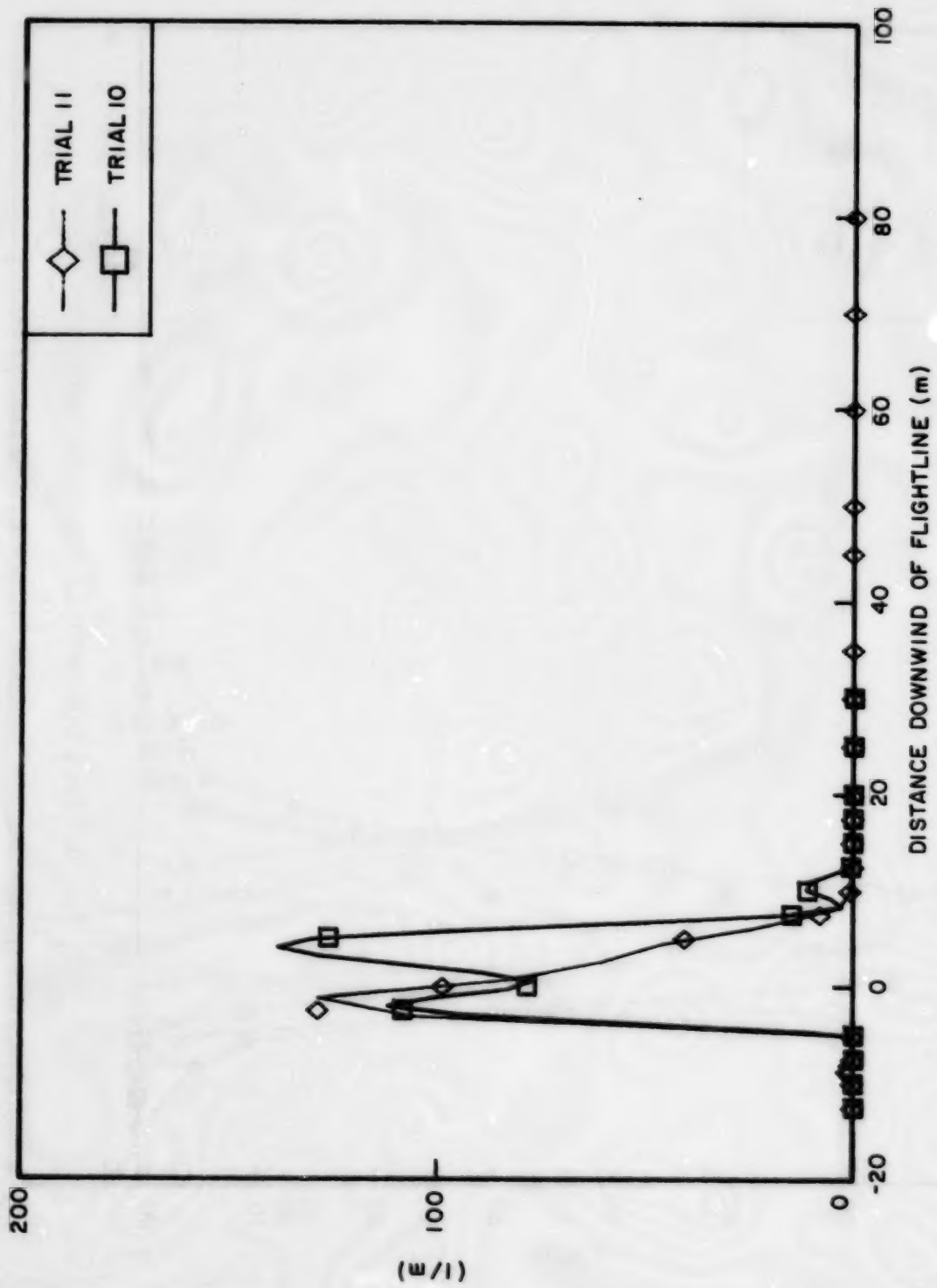


FIG. 3(c): NORMALIZED CROSSWIND DEPOSIT FROM GROUND-RIG SPRAYS

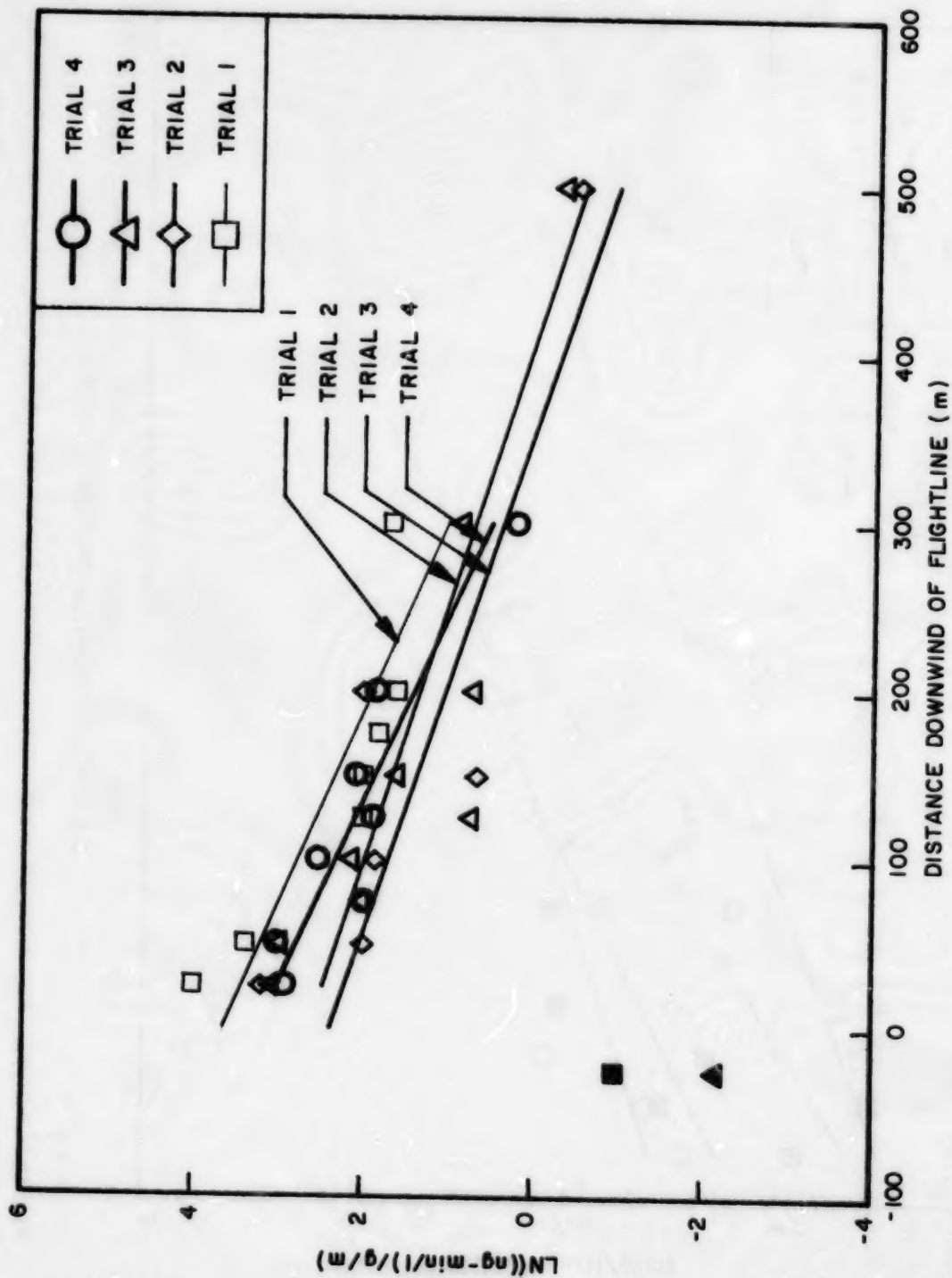


FIG. 4(a): NORMALIZED ATMOSPHERIC DOSAGE OF NON-VOLATILES AT 1.5 m AGL FROM AG-CAT SPRAYS

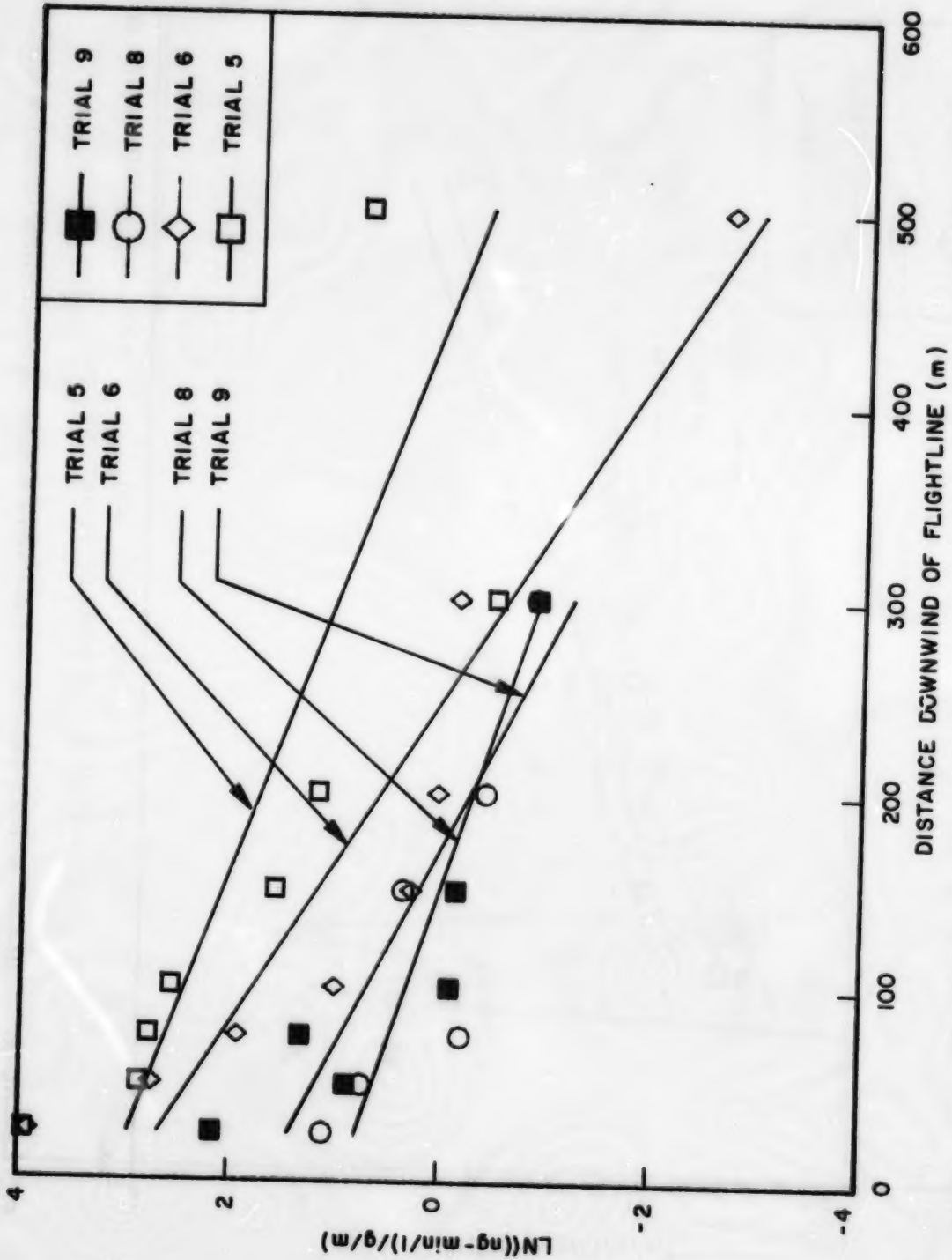


FIG. 4(b): NORMALIZED ATMOSPHERIC DOSAGE OF NON-VOLATILES AT 1.5 m AGL FROM PAWNEE SPRAYS

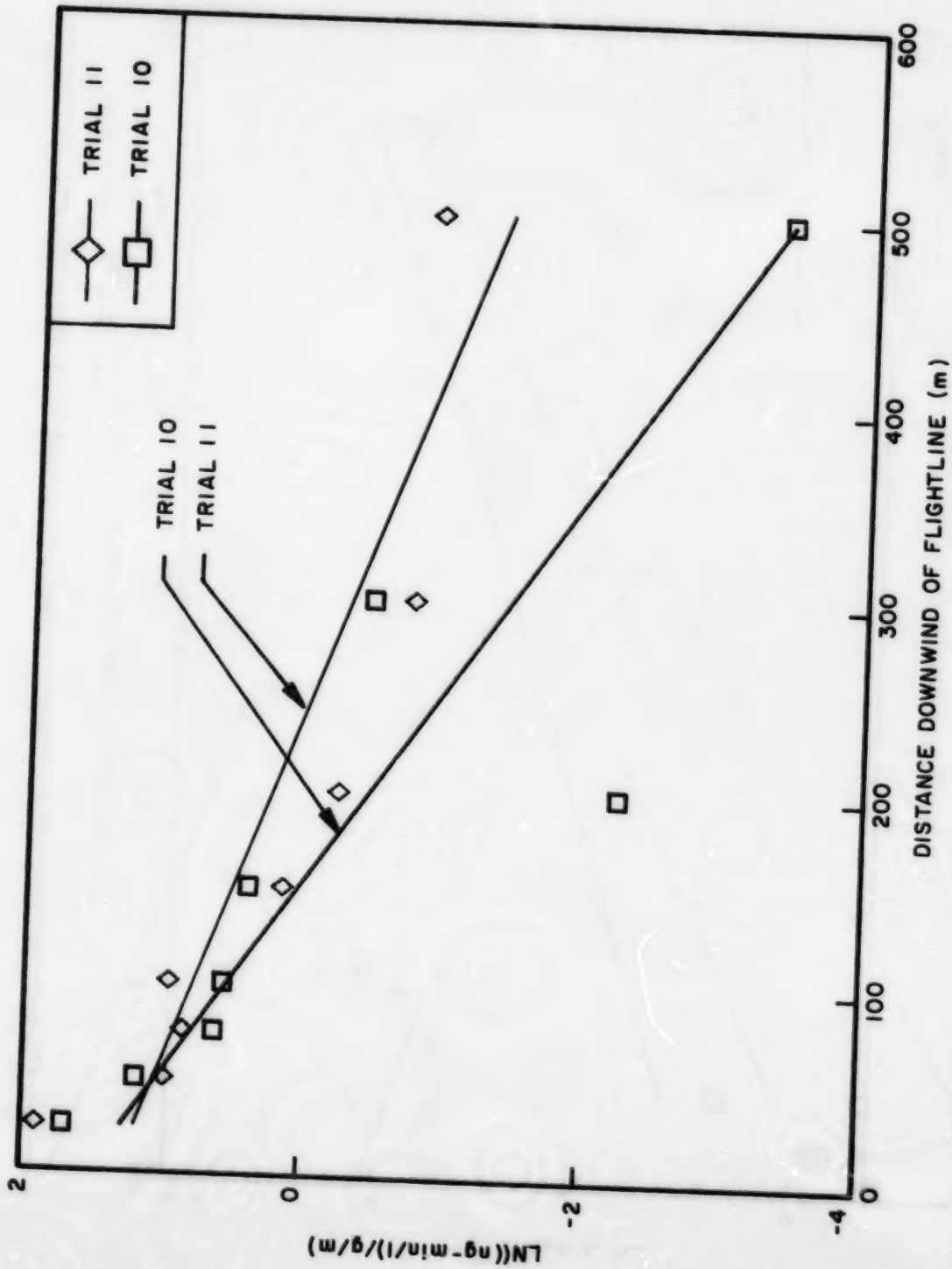


FIG. 4(c): NORMALIZED ATMOSPHERIC DOSAGE OF NON-VOLATILES AT 1.5 m AGL FROM GROUND-RIG SPRAYS

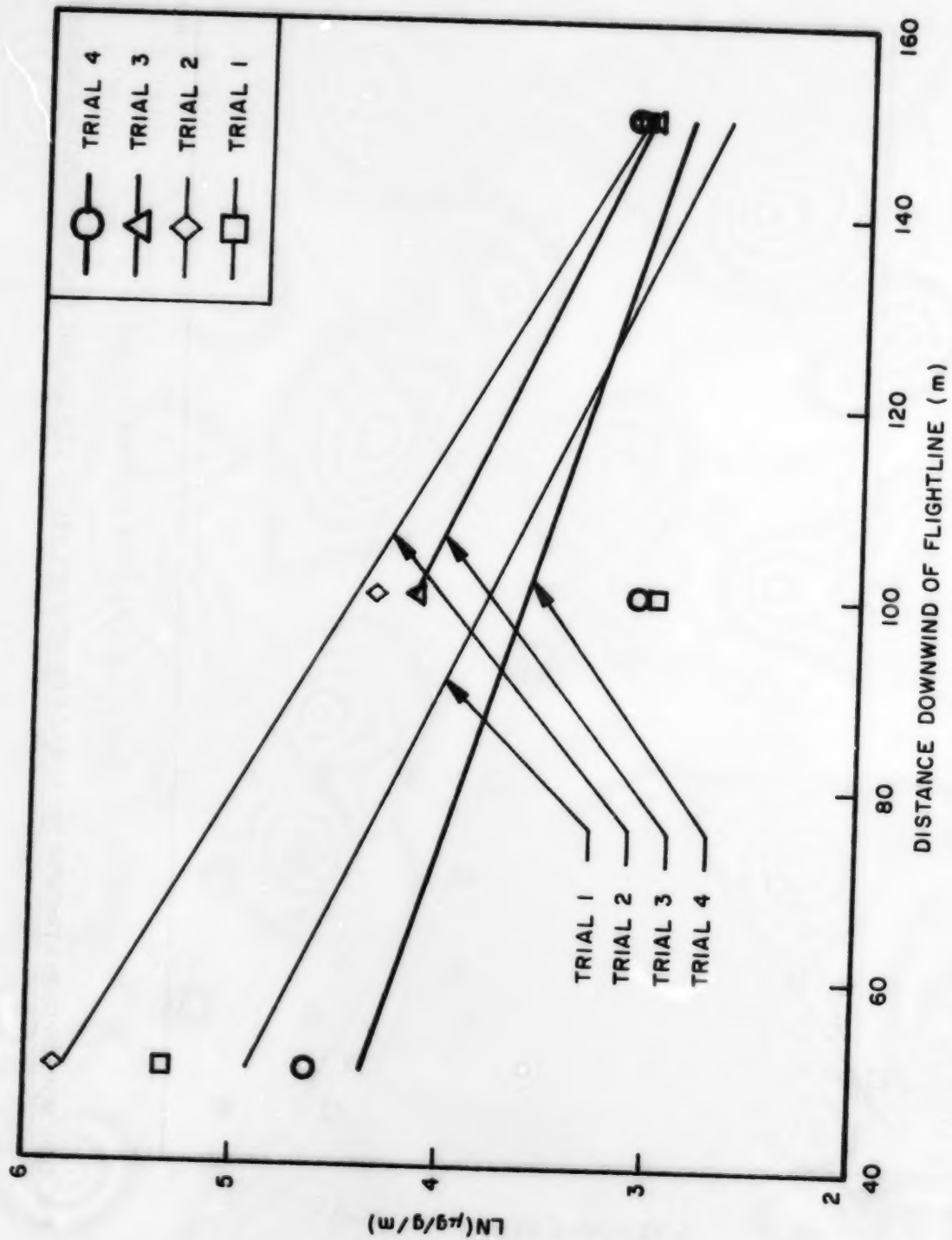


FIG. 5(a): NORMALIZED BYSTANDER DERMAL EXPOSURE FROM AG-CAT SPRAYS

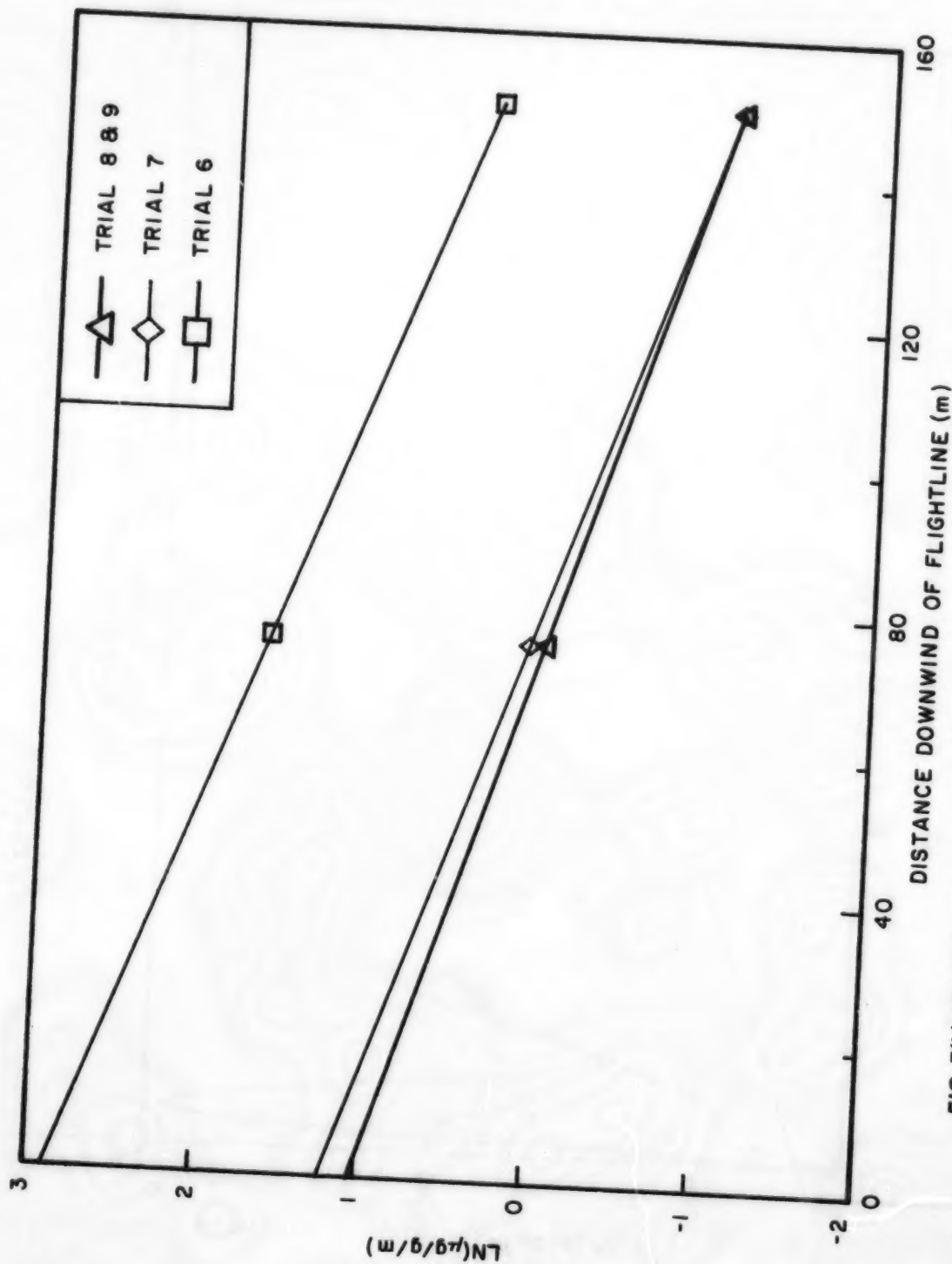


FIG. 5(b): NORMALIZED BYSTANDER DERMAL EXPOSURE FROM PAWNEE SPRAYS

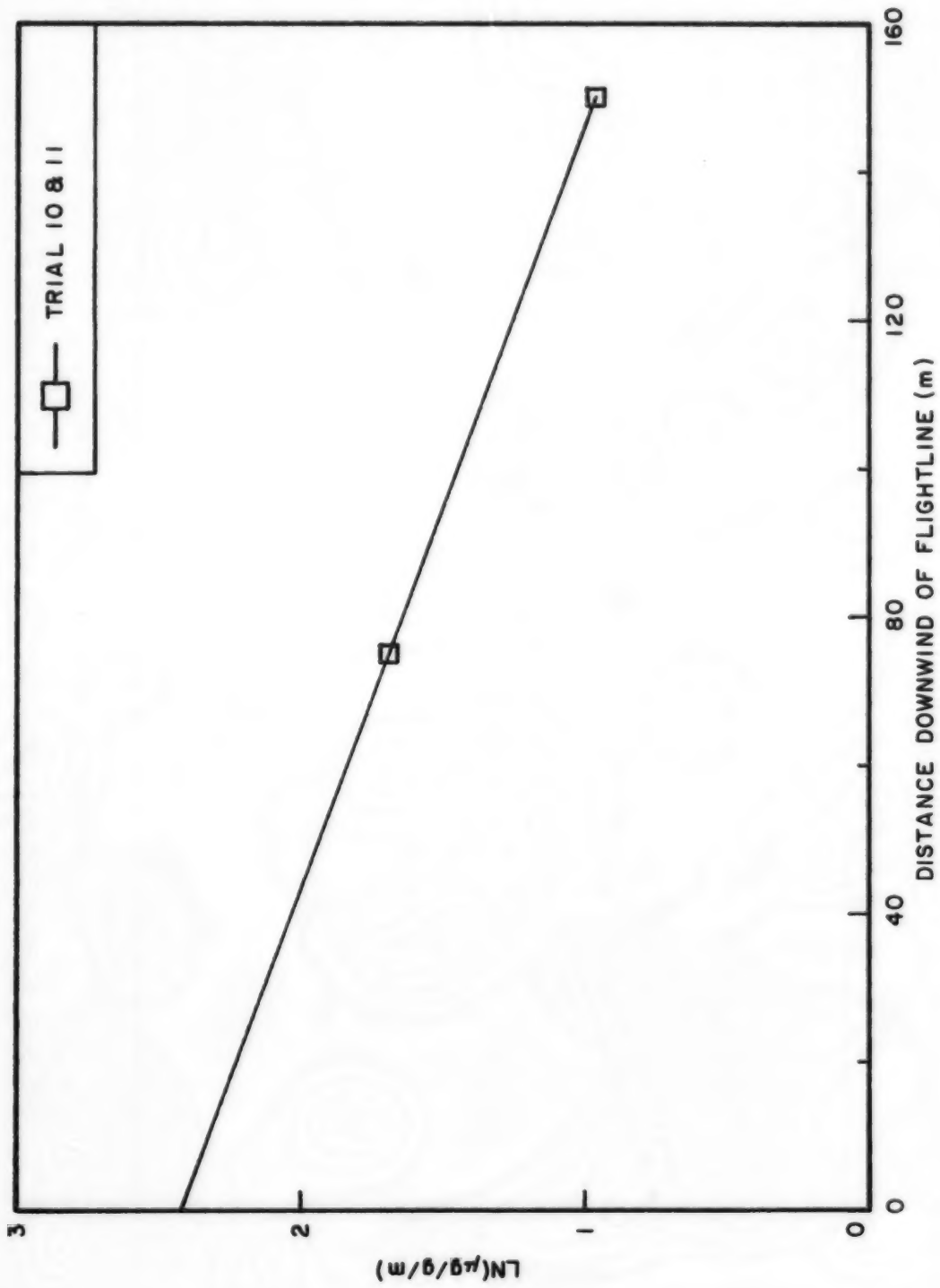


FIG. 5(c): NORMALIZED BYSTANDER DERMAL EXPOSURE FROM GROUND-RIG SPRAYS

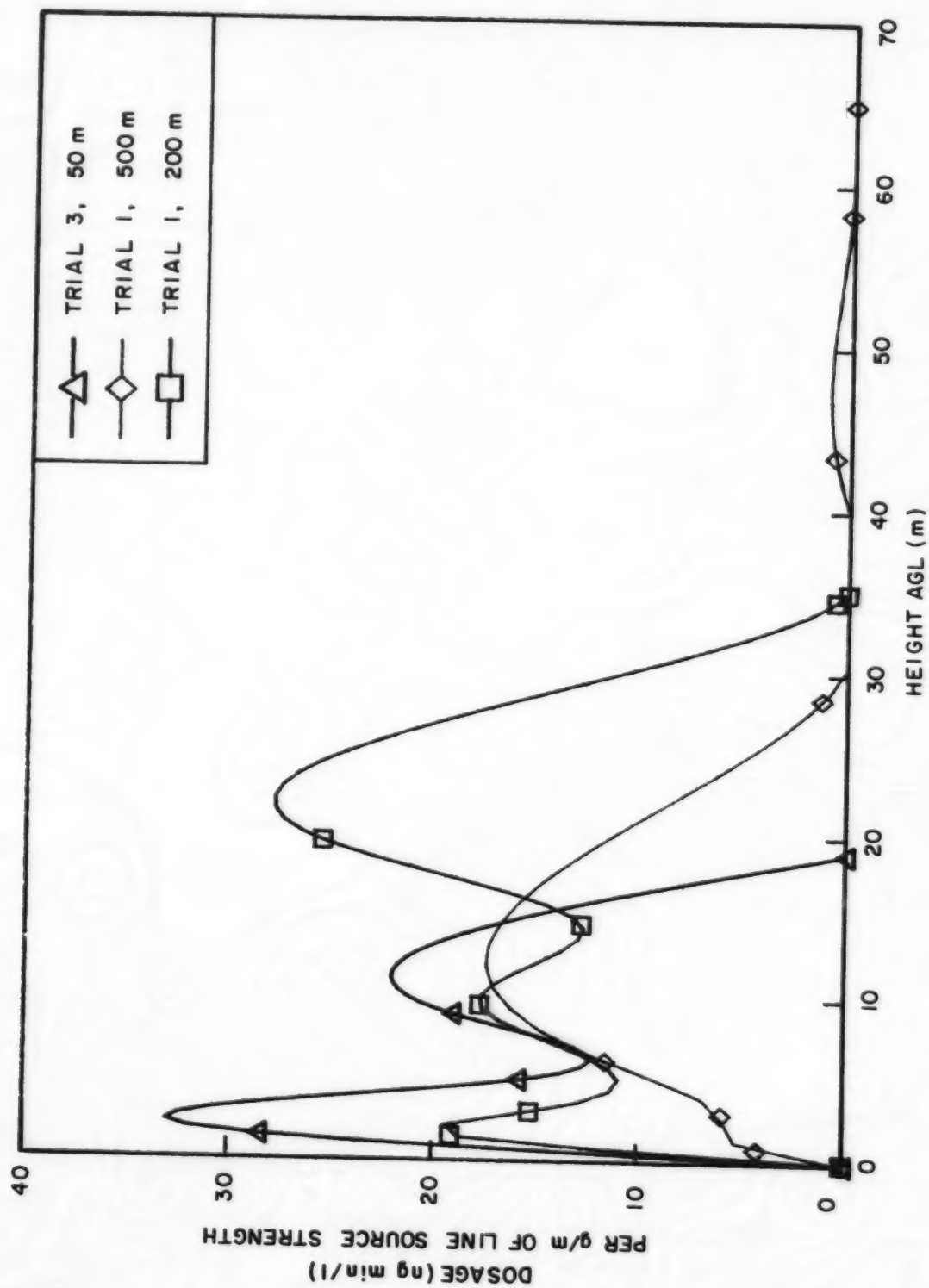


FIG. 6(a): NORMALIZED VERTICAL DOSAGE PROFILES FROM THE AG-CAT SPRAYS

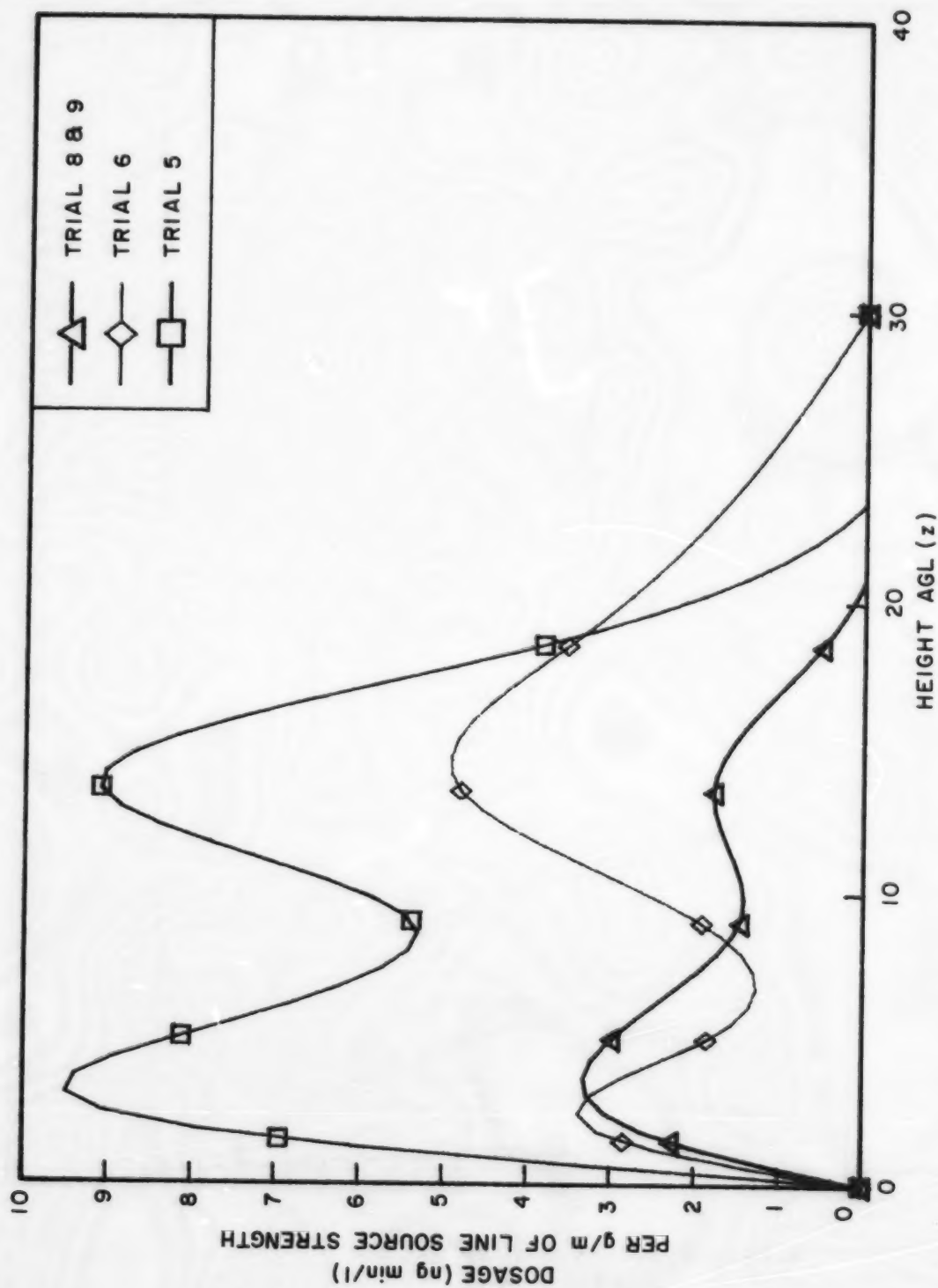


FIG. 6(b): NORMALIZED VERTICAL DOSAGE PROFILES AT 200 m FROM PAWNEE SPRAYS

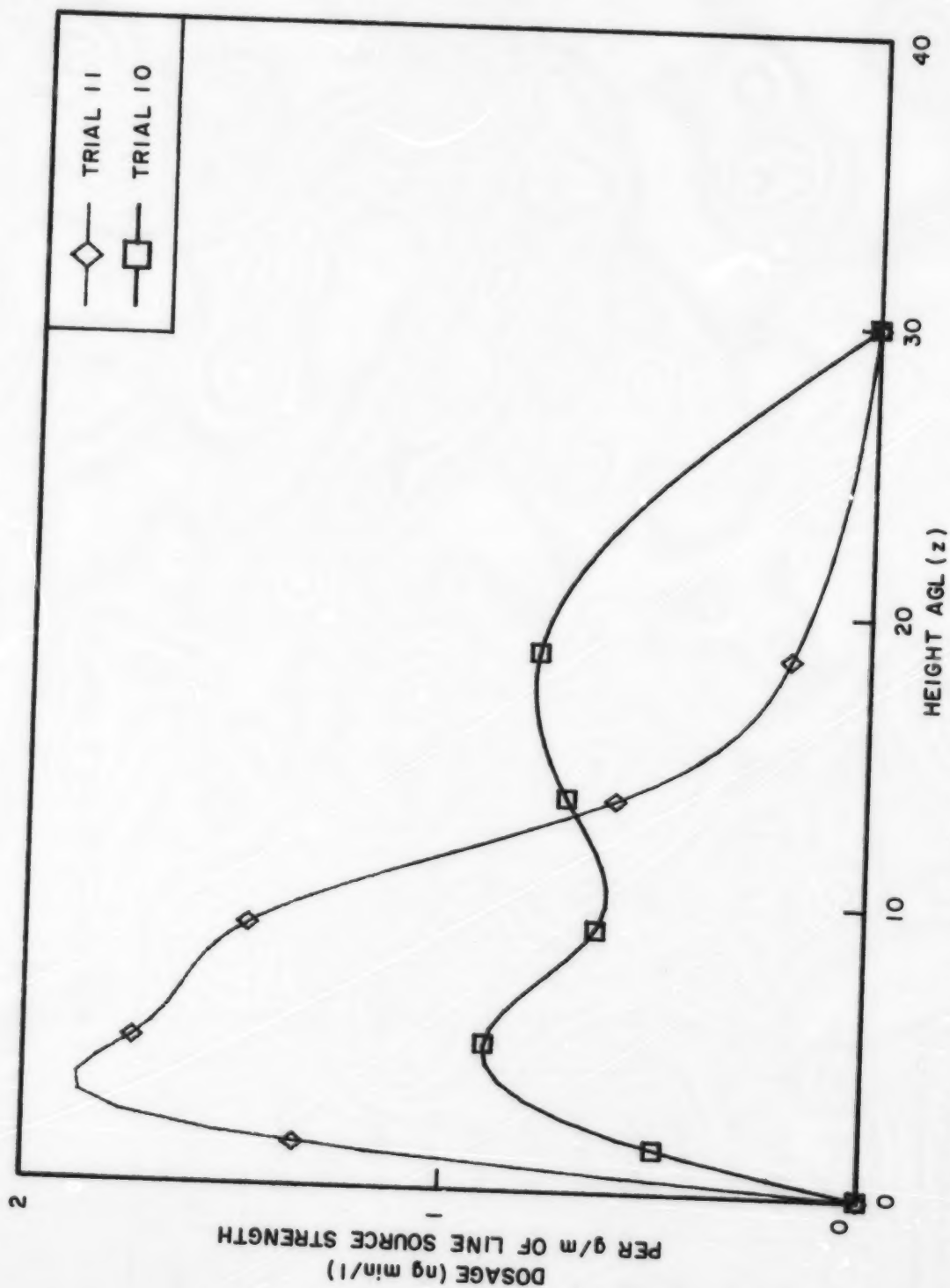


FIG. 6(c): NORMALIZED VERTICAL DOSAGE PROFILES AT 200 m FROM GROUND-RIG SPRAYS

APPENDIX I

ATMOSPHERIC SURFACE-LAYER STRUCTURE DURING THE SPRAY TRIALS

Trial	4.25 m agl ^a U ₁ (°M/ms ⁻¹)	8.6 m U ₂	17.2 m U ₃	17.2 m agl 4.3 m agl T ₃ - T ₁	R ₁ (8.5)	H = ρ C _p $\overline{w\theta}$ watts m ⁻²	u* (ms ⁻¹)	L (m)	V _d (cm s ⁻¹) at 4.2 m agl
1	225/3.64	4.16	4.63**	-0.291		12.3	0.301 (0.277 from U ₁ and U ₂)**	-228	1.7
2	312/4.91	5.25**	6.28**	-0.360		100.8	0.442	- 90.3	2.8
3	280/3.99	4.56	5.20**	-0.119		- 6.9	0.264	271	1.2
4	248/2.81	3.38	3.50**	-0.371		19.6	0.183	- 32.2	0.8
5	257/2.67	3.16	3.23	-0.358	-0.31	23.1	0.177	- 24.6	0.8
6	280/0.89	1.26	1.25	-0.188	-0.22	14.1	0.075	- 3.1	0.4
7	298/1.63	2.01	2.10	-0.264	-0.27	36.1	0.123	- 5.3	0.6
8	246/1.07	1.41	1.47	-0.370	-0.64	65.5	0.122	- 2.9	1.0
9	223/1.14	1.53	1.58	-0.499	-0.78	78.5	0.160	- 5.5	1.6
10	097/4.40	5.13	5.35	-0.616	-0.23	108.6	0.325	- 33.0	1.7
11	100/4.08	4.60	5.44	0.266	0.085	- 23.6	0.258	74.4	1.1

** Estimated from surface layer theory

a Metres above ground level

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SUMMARY/SOMMAIRE Wind drift, deposition and bystander exposure measurements from agricultural aircraft and ground-rig spray emissions over rural terrain using conventional spray booms and atomizers are presented. A single line was treated. The formulations were aqueous oil emulsions to simulate herbicide applications and aqueous wettable powder emulsions to represent fungicide sprays. Meteorological conditions varied from 'calm' thermally unstable to near-neutral moderately windy (4.9 ms^{-1} at 4 m above ground). Time-integrated atmospheric droplet concentrations (dosage) were measured at breathing height to 500 m downwind and vertically to drift cloud top at 200 and 500 m downwind. Analysis of field data disclosed initial ground deposit accounting for nearly 100% of the non-volatiles in the ground-rig emission, but only from 60 to 80% of the aircraft emission depending upon wind speed, in agreement with the data indicated bystander dermal exposures to non-volatiles at 75 m downwind increasing from $150 \mu\text{g}$ for the first swath to $600 \mu\text{g}$ after 10 swaths in light winds (2.8 ms^{-1} at 4 m agl). At 200 m the measured drift cloud mass from the aircraft sprays varied from 1 to 2% of the emission in light winds. In this connection, 90° nozzle orientation on the aircraft resulted in greater wind drift than trailing orientation. The wettable-powder drift data revealed that at and beyond 75 m where spray evaporation was essentially complete, the dermal exposure could be less than from herbicide sprays due to the possibility of particle rebound from collecting surfaces.				